Transactions on the Built Environment vol 55, © 2001 WIT Press, www.witpress.com, ISSN 1743-3509

Stress analysis of an ancient stupa in Sri Lanka in connection with its conservation

M.P. Ranaweera
Department of Civil Engineering,
University of Peradeniya, Sri Lanka

Abstract

Abhayagiri Stupa in Anuradhapura, Sri Lanka, built in the first century BC and subsequently enlarged, is a solid brick structure which had reached a height of 83 m at its heyday. Presently the Stupa is in ruins and is overgrown with vegetation, and a programme to conserve it is in progress. This paper presents results of an analytical study to find stresses in the Stupa and identify critical areas which need special attention in its conservation.

Analyses of the Stupa, under its self weight, were done by the finite element method. The dome of the Stupa was modelled as an axi-symmetric problem and its square chamber was analyzed as a three dimensional problem. The latter was analyzed with three configurations for a reinforced concrete ring beam at its top. The results showed that the stresses in the dome and the square chamber are small compared with strengths of the bricks used. There are some tensile zones, but with small tensile stresses which can be carried by the brickwork, unless it loses its strength due to exposure to elements. The introduction of a ring beam at the top of the square chamber has the beneficial effect of reducing the extent of the tensile zone and the maximum value of the tensile stress in the brickwork.

1 Introduction

In Sri Lanka, monumental structures called stupas have been built to honour Lord Buddha, and they are an indispensable feature of any Buddhist temple [1]. Stupas house sacred relics of Buddha, or mark the sacred spots at which some

Transactions on the Built Environment vol 55, © 2001 WIT Press, www.witpress.com, ISSN 1743-3509

important event connected with the religion had taken place, and they are venerated by the Buddhists. Their imposing, yet simple, features give one a feeling of stability, strength, nobility, and grandeur.

The oldest stupa in Sri Lanka is Thuparama, built by King Devanampiyatissa (250-210 B.C.) in the then capital city of Anuradhapura. With the passage of time more stupas have been built by the Kings, notable ones being Mirisevetiya and Ruvanveliseya by King Dutugemunu (161-137 B.C.), Abhayagiri by King Valagambahu (89-77 B.C.), and Jetavana by King Mahasen (A.D. 276-303). Jetavana, which attained a full height of around 120 metres, was at one time the third tallest structure in the world, surpassed only by the two great pyramids in Giza [2].

Stupas in Sri Lanka are brick structures, mostly solid. They are of different shapes, the common ones being bell shape, bubble shape, heap-of-paddy shape, and pot shape. The bell shape is the most common, and the large stupas are of heap-of-paddy shape. The latter is the most stable from a structural point of view [3], and the ancient builders have somehow arrived at this shape for the colossal stupas they built [2].

Due to foreign invasions and the shift of the capitals from one place to another, the ancient stupas were neglected and decay started. The decay would have followed a progressively worsening process initiated by cracking of the surface, followed by rain water penetration, animal infestation, vegitation growth and root penetration in cracks, and would have been compounded by surface water erosion .

Conservation of these ancient structures is of paramount importance and presently a conservation programme is being carried out by the UNESCO - Sri Lanka Project of the Cultural Triangle of the Central Cultural Fund. The conservation of the Abhayagiri Stupa is a major activity of this programme. This paper presents some structural analyses done in connection with the present conservation work of the Stupa.

2 Abhayagiri Stupa

Abhayagiri Stupa was built by King Valagambahu in the first century B.C. It was subsequently enlarged by other Kings and a major enlargement was done by King Parakramabahu (A.D. 1153-1186). Later it was abandoned and underwent decay (Fig. 1).

Abhayagiri Stupa is a solid structure, accurately set on North-South, East-West axes, having the usual components of a traditional stupa. It is composed mainly of burnt brick of various sizes with some inner regions filled with brocken brick pieces and earth.

Main components of the Stupa are shown in Fig. 2. In the Nineteenth Century, a survey of the Stupa was done by Smithers [4]. Several surveys has been done since then, and according to the latest survey by Dampegama [5] the dome of the Stupa is a solid of revolution, represented by the equation,

$Z = 50.77112 - 0.001548\ R - 0.019566\ R^2$,

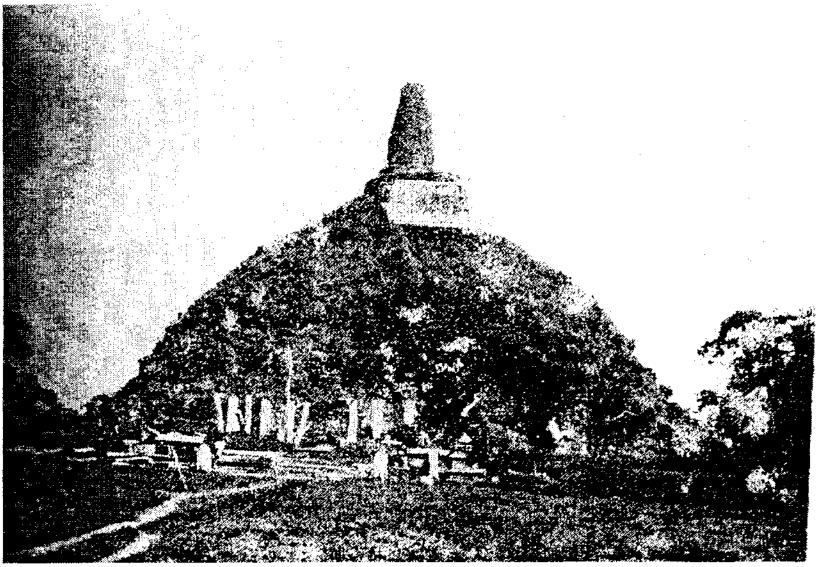


Figure 1: Abhayagiri Stupa after decay.

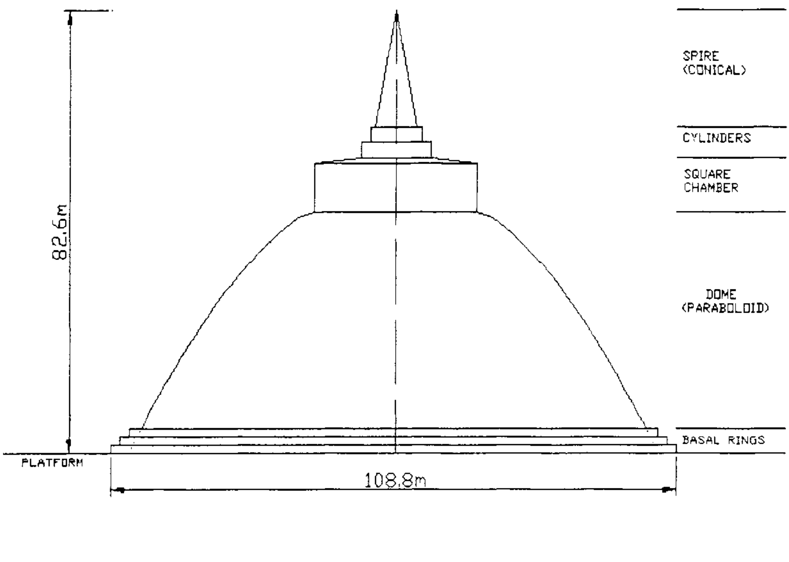


Figure 2: Main components of the Stupa.

constant Z. This, almost paraboloidal, shape of the dome is closest to the traditional heap-of-paddy shape, which, as mentioned earlier, is the best shape for the dome of a stupa from a structural point of view.

The Stupa is founded on rock and is encircled by a stone paved square platform. Presently the spire is broken and reaches only upto a level 73.0 m from the platform, and the conjectural height to the top of the spire is 82.6 m [5]. The Stupa has three basal rings, the outer one having a diameter of 108.8 m. The basel rings have been constructed outside the dome, and they do not support the weight of the superstructure. The dome rises to a height of 45 m from the platform, and its lower and upper diameters are 101.8 m and 34.2 m, respectively. At the top it has been flattened to take the square chamber, which is a solid of square cross section (31 m x 31 m) and height 10 m. Two cylindrical members above the square chamber have a height of 3 m each, and diameters of 13.4 m and 10.0 m. The conical spire at the top has a base diameter of 8.0 m and a height of 21.6 m.

3 Conservation of Abhayagiri Stupa

Major part of the Abhayagiri Stupa conservation work involves its dome and the square chamber. The dome, which is covered with vegitation, has to be cleaned and a new layer of brick is to be added, on top of old bricks, where necessary. The square chamber has to undergo major repairs as some parts of it had undergone serious damage. In connection with this conservation work, some analyses were done to identify weak regions of the structure and suggest remedial action.

4 Analysis of Abhayagiri Stupa

The dome and the square chamber of the Stupa were analysed using the Finite Element Method, employing the general purpose finite element package SAP2000 [6].

4.1 Material properties and loading

Limited tests conducted on oven dry samples cut from ancient bricks used in the Stupa gave the following mechanical properties.

Cylinder compressive strength = 8500 kPa, split cylinder tensile strength = 850 kPa, Young's modulus = 4.5 GPa, Poisson's ratio = 0.25, and specific weight = 16.9 kN/m^3.

Transactions on the Built Environment vol 55, © 2001 WIT Press, www.witpress.com, ISSN 1743-3509

Both the dome and the square chamber were analysed under loading due to self weight. A value of 19.6 kN/m^3 was used for the specific weight of bricks to account for water absorption.

4.2 Analysis of the dome

Full Stupa was analysed as an axisymmetric solid using the model shown in Fig. 3, to determine the stresses in the dome. Four-node and three-node axisymmetric elements (ASOLID elements) of SAP2000 were used in the analysis. The model was fixed at the bottom.

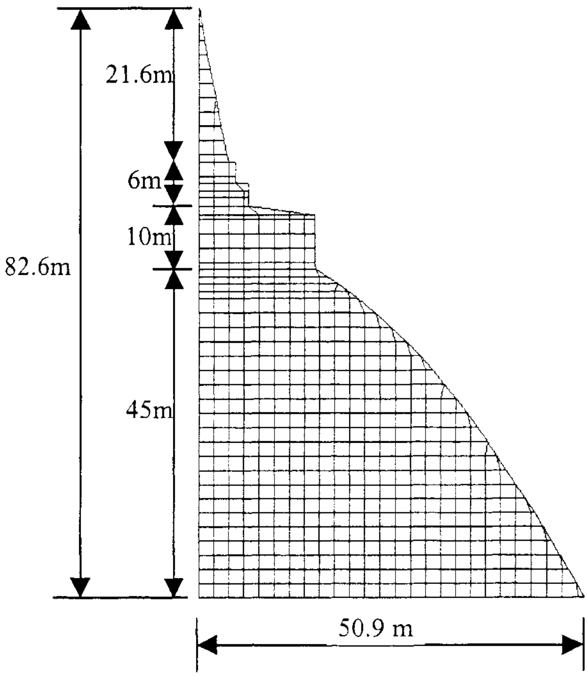
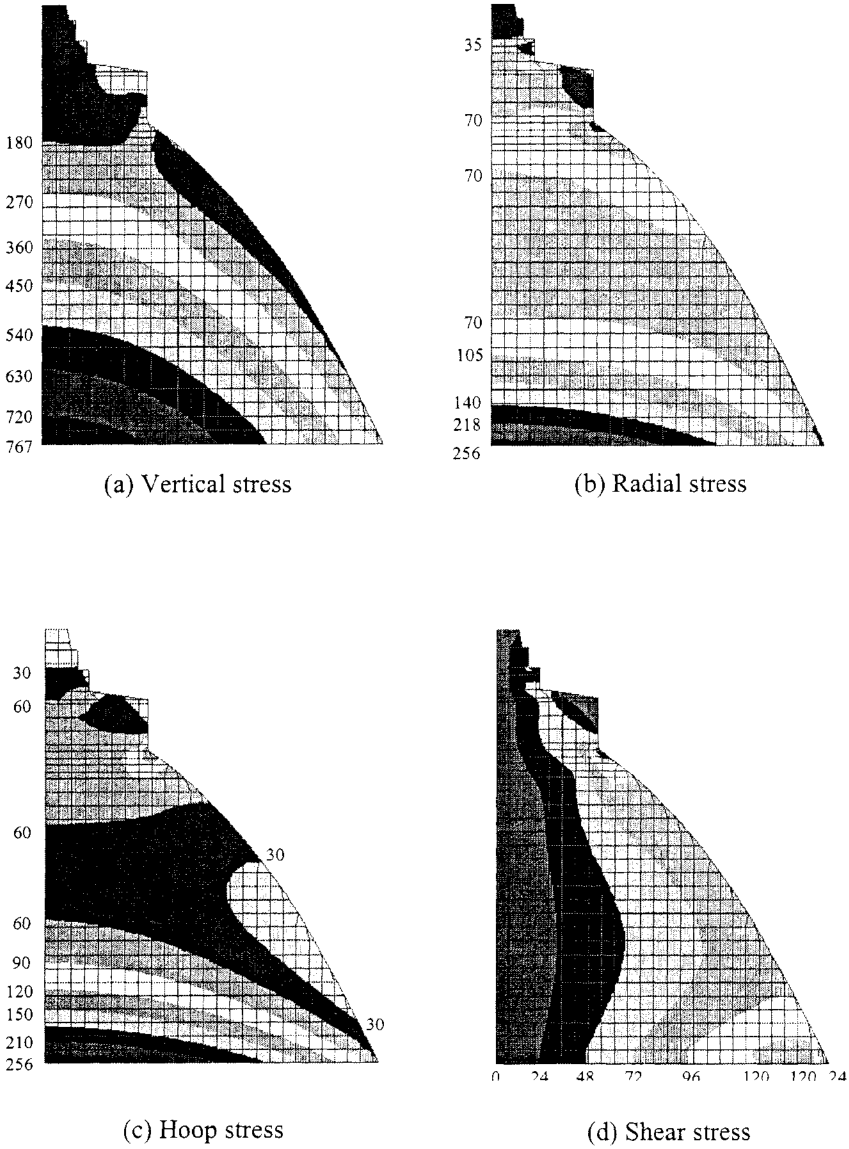


Figure 3: ASOLID model for the dome.

Contours obtained for vertical, radial, hoop, and shear stress components are given in Figs. 4a, 4b, 4c, & 4d respectively. Figure 4a shows compressive vertical stress increasing steadily from top to bottom of the structure reaching a maximum of 767 kPa at the centre of the base. This is nearly one and half times the average compressive stress (516 kPa) at the base, and is less than one tenth of the compressive strength (8500 kPa) of ancient bricks. Radial stresses (Fig. 4b) and hoop stresses (Fig. 4c) are also compressive throughout the dome reaching a maximum value of 256 kPa at the centre of the base. The maximum shear stress obtained is 120 kPa at the outer edge of the base (Fig. 4d).



(a) Vertical stress

(b) Radial stress

(c) Hoop stress

(d) Shear stress

Figure 4: ASOLID model –Stress contours (kPa).

Transactions on the Built Environment vol 55, © 2001 WIT Press, www.witpress.com, ISSN 1743-3509

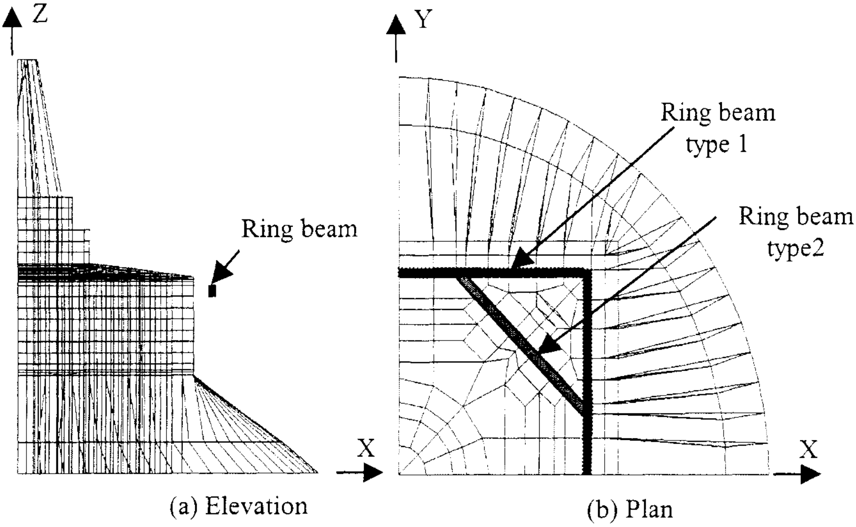


Figure 5: SOLID model for square chamber.

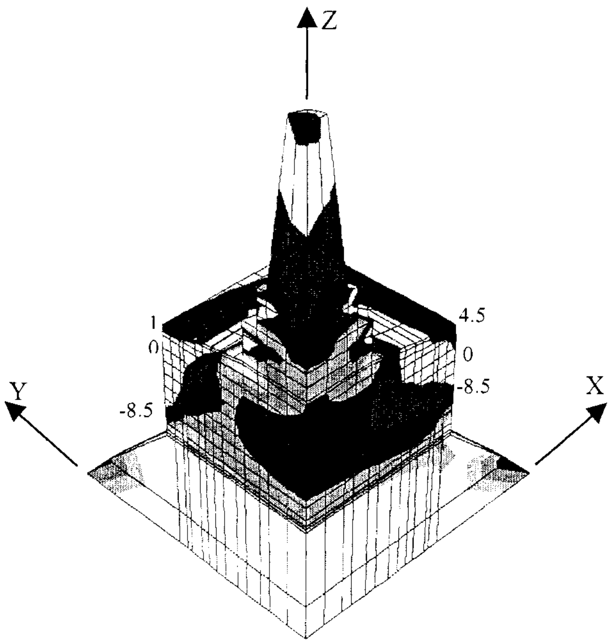
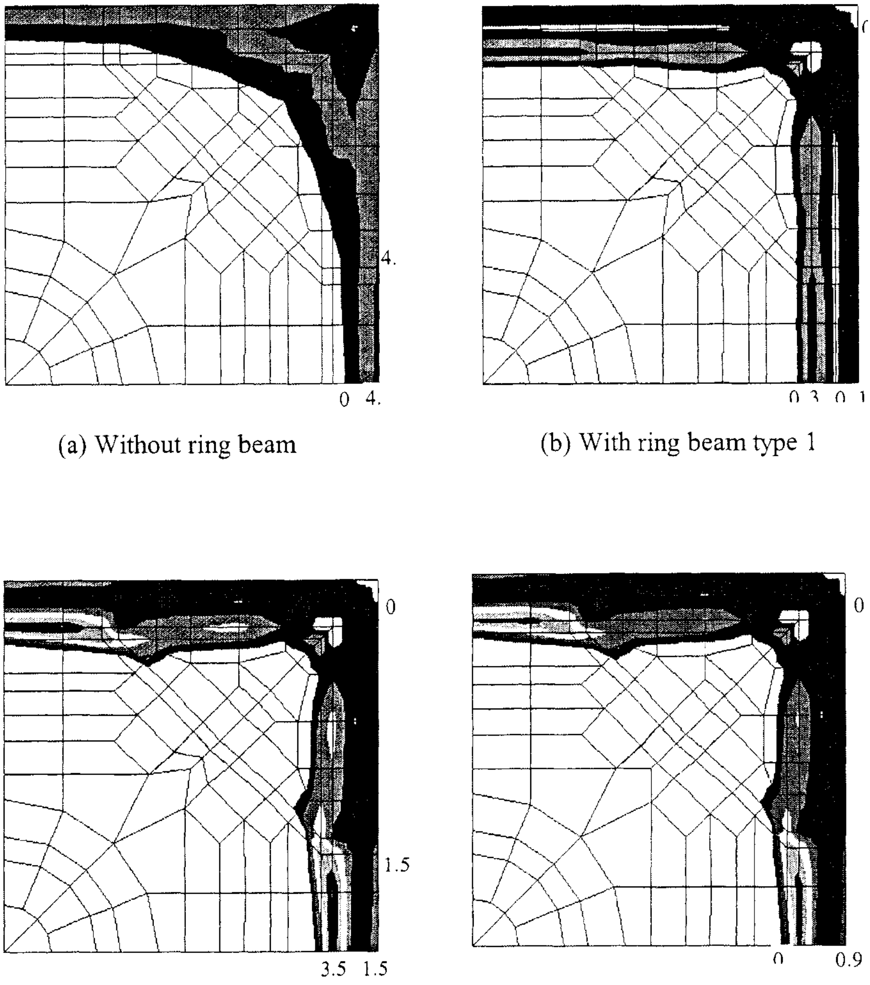


Figure 6: SOLID model (no ring beam)-Contours of Syy (kPa).

Transactions on the Built Environment vol 55, © 2001 WIT Press, www.witpress.com, ISSN 1743-3509



(a) Without ring beam

(b) With ring beam type 1

(c) With ring beam type 2

(d) With ring beam type 3

Figure 7: SOLID Model –Tensile zones at top (kPa).

4.3 Analysis of the square chamber

The square chamber was analysed with a 3D model (Fig. 5) using 8-node brick elements (SOLID elements). Due to the symmetry of the structure about the North-South and East-West axes, only a quarter of the square chamber was considered in the analysis, together with a part of the dome.

Contours of Syy stresses obtained with this 3D model with all elements composed of brick material (Fig. 6), show some tensile regions at the top of the square chamber, with a maximum tensile stress of about 4.5 kPa. The bricks are capable of supporting these tensile stresses unless they loose their strength due to

Transactions on the Built Environment vol 55, © 2001 WIT Press, www.witpress.com, ISSN 1743-3509

exposure to elements. As this is a reality, it was decided to introduce a reinforced concrete ring beam of rectangular section (1140 mm x 500 mm) at the top, as shown in Fig. 5. Three geometries were considered for this ring beam. The beam type 1 is rectangular in plan and the beam type 2 is octagonal. Beam type 3 is a combination of both.

The tensile stress (maximum stress) regions at the top of the model with these three types of ring beams are compared with the zone obtained without the ring beam, in Fig. 7. It is seen that, as to be expected, the ring beams have reduced the tensile stress in the brickwork around them, with ring beam type 3 giving the most beneficial effect. However considering practical aspects, the ring beam type 2 was selected for implementation.

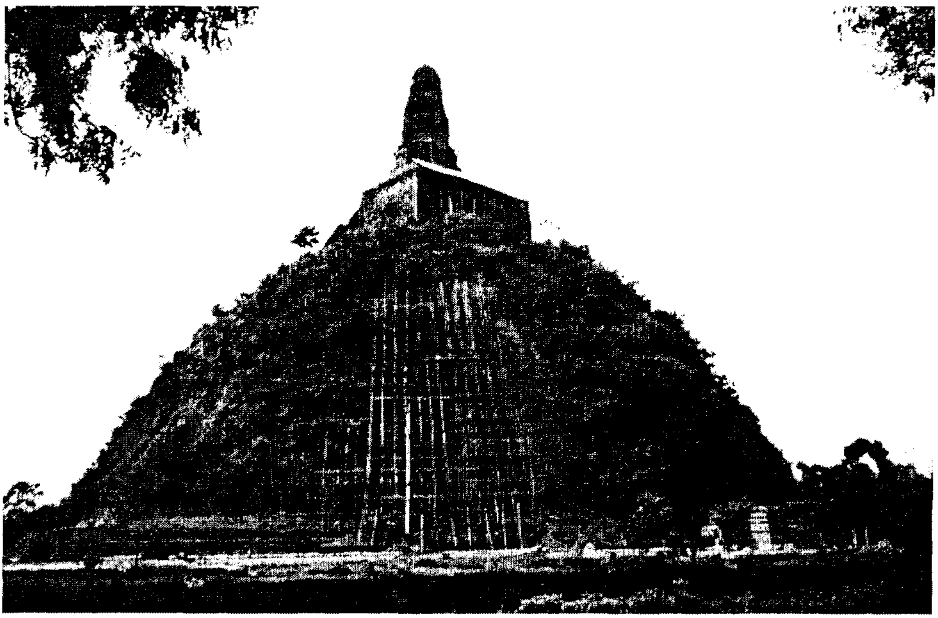


Figure 8: Stupa under conservation.

5 Conservation work

Conservation work is now going on with minimum intervention to existing status. Where brick structure in the dome is found showing loose bricks, they are removed and rebuild with new mortar after cleaning the surface. Where there is heavy erosion, new bricks, which are of the same dimensions as the old, are laid to a thickness of about 1 m, and the surface layer is pointed. No attempt is made to restore the dome to the original shape. In the case of the square chamber where large portions have collapsed, reconstruction is done to get the original shape. To prevent any likelyhood of cracking that can take place in tensile regions found from the analyses, a reinforced concrete ring with stainless steel reinforcements will be introduced. Stupa undergoing conservation is shown in Fig. 8.

6 Conclusions

The analyses performed showed that the stresses in the Stupa are well below the strengths of the bricks used. The dome is wholly under compression, with the maximum stress value well below the compressive strength of ancient bricks. Some regions of the square chamber are in tension, but with very low levels of stress which can easily be taken by ancient bricks. In this case, the use of modern tools of computation has enabled the conservation of this ancient structure with minimum intervention.

7 Acknowledgements

This study was embarked on at the request of Dr. Roland Silva, former Director General of the Central Cultural Fund, and the author wishes to thank him and his staff for all the help given. Thanks are also due to Mr. Gemunu Silva, General Manager of the State Engineering Coorporation, who is the Technical Advisor to the Abhayagiri Project. Assistance from Messrs. P. Partheepan and Keerthi Perera, of the Compter Aided Design Laboratory, in the preparation of this paper is also gratefully acknowledged.

References

[1] Paranavitana, S., *The Stupa in Ceylon*, Colombo Museum, 1988.

[2] Silva, R., The Engineering principles behind the largest brick monuments of the ancient world: the colossal stupas of Sri Lanka, *Perspectives in Archeology: Leelananda Prematilleke Festichrift*, Peradeniya, 1982.

[3] Ranaweera, M.P., Stresses in stupas of different shapes, *Proceedings of the Annual Research Sessions*, University of Peradeniya, 1998.

[4] Smithers, J.G., *Architectural Review of Anuradhapura*, 1894.

[5] Dampegama, S.D.P.J., *Final Report of the Abhayagiriya Stupa Survey*, Institute of Surveying and Mapping, Diyatalawa, 2001.

[6] Wilson, E.J. & Habibullah, A., *SAP2000 – Integrated Finite Element Analysis and Design of Structures*, Computers & Structures Inc., California, 1998.